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AN OVERVIEW OF THE AAW SIMULATOR: A KNOWLEDGE-BASED TEWA FOR MULTIPLE SHIPS AND MULTIPLE THREATS

by

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ABSTRACT

This document presents an overview of a knowledge-based threat evaluation and weapon assignment (TEWA) testbed referred to as the AAW simulator. This testbed is used to generate weapon assignment reactions in which the deployment of hardkill and softkill weapons is integrated with ship movements such as rotation. It incorporates efficient weapon assignment algorithms for single and multiple ship cases. Resource allocation results are presented for the knowledge-based TEWA of a single, maneuverable ship attacked by twelve anti-ship missiles and those of four ships attacked each by a pair of anti-ship missiles.

RÉSUMÉ

Ce document présente une vue d'ensemble du banc d'essai appelé "AAW Simulator", qui est un système à base de connaissances conçu pour effectuer l'évaluation des menaces et l'allocation des ressources. Les allocations d'armes sont caractérisées par le déploiement de missiles sol-air, de canons de calibre moyen, de canons à tir rapide et de leurres ou de brouilleurs qui sont tous assujettis aux mouvements du navire, notamment au changement de direction du navire. Ce document présente le système à base de connaissances pour un seul navire, lorsque plusieurs navires doivent se défendre d'une attaque aérienne. Les résultats de l'allocation des ressources sont présentés pour un scénario dans lequel un seul navire subit l'attaque de douze missiles anti-navires et un scénario dans lequel huit missiles anti-navires attaquent quatre navires.

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EXECUTIVE SUMMARY

The Threat Evaluation and Weapon Assignment (TEWA) is an important function in the command and control system of an Anti-Air Warfare (AAW) frigate or destroyer, since it ranks the air threats of the track database system and assigns a hardkill weapon or a softkill weapon to each threat in order to destroy or decoy it. This document presents an overview of a TEWA testbed, referred to as the AAW simulator, to appreciate its overall capabilities.

The AAW simulator simulates sensors, weapons and command and control systems on multiple warships. A sensor data fusion process generates air tracks from the AAW environment for a knowledge-based TEWA and the latter initiates hardkill or softkill actions which change the AAW environment. The AAW simulator is a closed-loop simulator in the sense that the weapon systems interact with the knowledge-based TEWA. The knowledge-based TEWA assigns a weapon, such as chaff to a threat; the effect of the weapon on the threat is calculated; this effect is detected by the ship's sensors and the new sensor tracks which are generated are resubmitted to the TEWA, hence closing the loop.

The AAW simulator is primarily intended to be a research tool for studying the behaviour of a knowledge-based TEWA and obtaining quantitative results about interference between hardkill and softkill weapons, fratricide and other AAW problems involved in the defence of several warships from air attack. The research and results described in this memorandum will increase DREV's capability to define the requirements of the Situation, Threat Assessment and Resource Management (STARM) application foreseen for the major Advanced Shipboard Command and Control Technology project (ASCACT) D6195. The ASCACT project is crucial for the Frigate Life EXtension program (FELEX).

LIST OF ACRONYMS

AAW	: Anti-Air Warfare
APAR	: Active Phased Array Radar
ARM	: Anti-Radiation Missile
ASM	: Anti-Ship Missile
ASW	: Antisubmarine warfare
ASuW	: Antisurface Warfare
ATMS	: Automatic Track Management System
C3	: Command, Control and Communications
CIWS	: Close-In Weapon System
CPA	: Closest Point of Approach
CPF	: Canadian Patrol Frigate
CRE	: Candidate Reaction Evaluation
CWI	: Continuous Wave Illuminator
DLF	: A Passive Decoy which is also known as 'the rubber duck'
DND	: Department of National Defence
DREV	: Defence Research Establishment Valcartier
DSS	: Directorate of Supply and Services
ECM	: Electronic Countermeasures
ESM	: Electronic Support Measures
HOJ	: Home-On-Jam
HUMBLE	: A non real-time knowledge-based shell
IR	: Infrared
IRST	: Infrared Search and Track
KBS	: Knowledge-Based System
LINK 11	: NATO standard datalink for ASW, ASuW and AAW communications
LINK 16	: Improved LINK 11 system for AAW communications
LRR	: Long-Range Radar
MARCOM	: Maritime Command
MLC	: Missile Launch Controller
NATO	: North Atlantic Treaty Organization
NILE	: NATO Improved Link Eleven System
RCS	: Radar Cross Section
SAM	: Surface-to-Air Missile
SDFP	: Sensor Data Fusion Processor

SMALLTALK	: An object-oriented computer language that originated in the 1980s.
S/N	: Signal-to-Noise ratio
STIR	: Signal (Separate) Tracking and Illuminator Radar
TCSC	: Thomson CSF Systems Canada
TEWA	: Threat Evaluation and Weapon Assignment
TRUMP	: Tribal Class Update and Modernization Project
TTGI	: Time to Target Intercept

1.0 INTRODUCTION

The threat evaluation and weapon assignment (TEWA) is an important function in the command and control system of an anti-air warfare (AAW) frigate or destroyer since it ranks the air threats in the track database according to criteria depending on the track and the ship and assigns a hardkill weapon or a softkill weapon to each threat in order to destroy or decoy it. This document presents an overview of a knowledge-based threat evaluation and weapon assignment (TEWA) testbed referred to as the AAW simulator. A detailed description of the knowledge-based system and its simulation environment is given in Refs. 1-4. However, in most of these references, the description is at the design level and consequently it is rather tedious to appreciate the overall capabilities of this testbed. The high level description presented in this document should fulfill that goal.

The knowledge-based TEWA was developed for a single stationary AAW destroyer attacked by anti-ship missiles. In a subsequent software development, TEWA reactions were built for this knowledge-based system involving ship rotations before deployment of hardkill and softkill weapons. In addition to integrating the TEWA hardkill and softkill reactions with the ship maneuvers, an attempt was made to close the loop between knowledge-based TEWA decisions, hardkill and softkill deployment, the effect of this deployment on the AAW environment and subsequent TEWA decisions. Consequently, an AAW simulator was developed in SMALLTALK 80 (Refs.5-8) simulating sensors, weapons and command and control systems on multiple warships. A sensor data fusion process generated air tracks from the AAW environment of the AAW simulator for a knowledge-based TEWA and the latter initiated hardkill or softkill deployment which changed the AAW environment as a result of these actions. The AAW simulator is primarily intended to be a research tool for studying the behaviour of a knowledge-based TEWA and, more generally, command and control issues in single ship or multiple ship air attack scenarios.

The knowledge-based system, sensor and weapon modules of the AAW simulator were coded in SMALLTALK and the simulator was required to execute four acceptance tests:

1. *acceptance test number one* consisted of two warships and a merchantman attacked by fourteen threats,
2. *acceptance test number two* consisted of one warship attacked by twelve threats with airborne jamming,

3. *acceptance test number three* consisted of one warship again attacked by twelve threats but without airborne jamming and
4. *acceptance test number four* consisted of four warships attacked by eight anti-ship missiles.

The document is organized as follows. Section 2 describes the modelled entities of the AAW simulator except the TEWA module which is described in Section 3. Section 4 gives a summary of the results obtained from acceptance tests two and four as generated by the AAW simulator.

The work was carried out at DREV from September 1992 to May 1995 under project 1ae "Shipboard Command and Control".

2.0 THE ANTI-AIR WARFARE SIMULATOR

In this section, a description is given of all the modelled entities of the AAW simulator except the TEWA module. The TEWA module is the heart of the AAW simulator and it deserves a separate section. The TEWA is described in section three. The modelled entities are described below in the following sections and have been designed to support the TEWA module. Fig. 1 shows a functional block diagram of the AAW simulator. It comprises the following entities:

1. the surveillance radar model
2. the Fire-Control Radar (FCR) model
3. the Electronic Support Measures (ESM) system
4. the Infrared Search and Track System (IRST)
5. the Surface-to-Air Missile (SAM) model
6. the threat model
7. the chaff and chaff controller models
8. the naval gun and Close-In-Weapon System (CIWS) model
9. the tracking processor
10. the Continuous Wave Illuminator (CWI)
11. the Sensor Data Fusion Processor (SDFP)
12. the fire-control processor
13. the Missile Launch Controller (MLC)
14. the jammer
15. the sensor management processor
16. the internal communication system
17. the external communication system
18. the force resource data fusion processor
19. the ship course model
20. the TEWA processor (described in the next section)

The following sections describe the modelled entities.

2.1 The Surveillance Radar Model

The AAW simulator has a surveillance radar model which can simulate conventional long range and medium range radars. The radar has a rotating parabolic antenna with a fixed scanning rate so that only rotating antenna surveillance radars may be simulated. The model includes the frequency, power, pulse characteristics, target radar cross section and range as factors contributing to the signal-to-noise ratio of the echoes received at the radar antenna. Detection of anti-ship missile threats is accomplished according to a Swerling model where the signal-to-noise ratio is calculated for the returning pulses and a detection occurs when the ratio exceeds a threshold. The detection test is performed at the scanning rate. Noise terms are added to the range and bearing estimates coming from the surveillance radar model. Smeared values of range and bearing are sent to the radar tracking processor.

2.2 The Fire-Control Radar Model

In the fire-control radar model, the azimuth and elevation slewing times are modelled assuming a constant slewing speed. The detection domain is limited in range and elevation with azimuth blind zones (obstruction from the ship's superstructure). Every threat within these range, azimuth and elevation windows is a candidate for detection. The signal-to-noise ratio (S/N) is calculated as a function of radar parameters : frequency, power, pulse width, target radar cross section and range. When the signal-to-noise ratio exceeds a certain threshold, a target detection occurs. Among the detectable targets, the fire-control radar locks onto the lowest one in elevation. If there is no detection, the search process in elevation is repeated periodically. Once a target has been detected, lock cannot be transferred to a second target although the initial target can be lost by the fire-control radar, i.e., a target is lost if it flies into a fire-control radar blind zone. A locked-on target is periodically checked for detectability. In addition, perfect discrimination is assumed when two targets have the same bearing and similar range and elevation. This means that the fire-control radar of the AAW simulator will track one of these targets and stay locked onto the same target during the extent of the air engagement.

The fire-control radar provides target velocity (vx, vy, vz) and position (x, y, z) as an output as well as an estimate of the measurement error. The data provided to the sensor data fusion processor from the fire-control radar model is smeared by the addition of noise while the data sent to the missile launch controller and the naval gun does not have errors associated with it. A very accurate fire-control solution is required for intercepts of air targets by surface-to-air missile (SAM) systems and guns. Therefore, any successful SAM system or gun system requires very accurate fire-control radar data as input to calculate a fire-control solution.

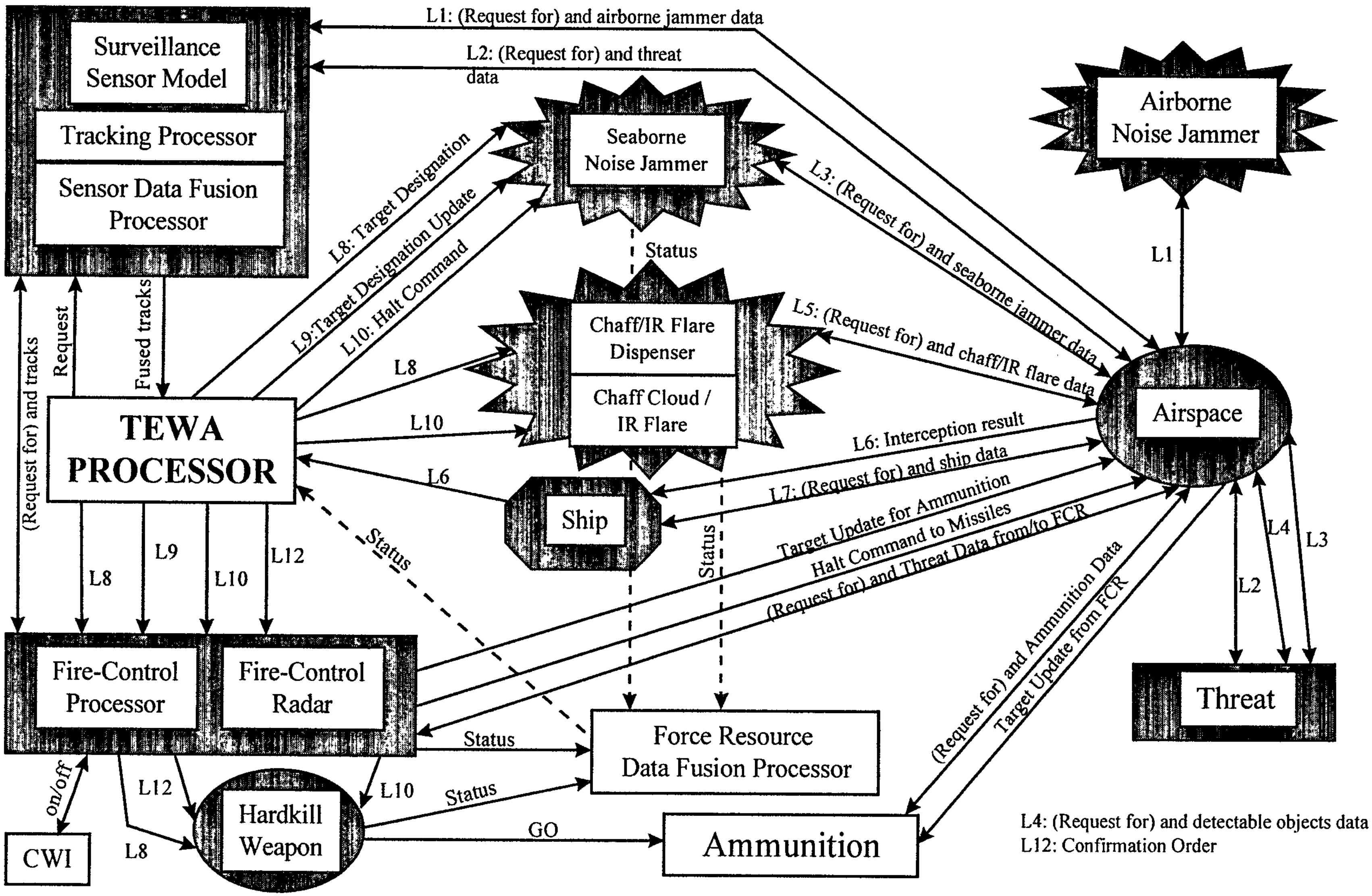

FIGURE 1 - The AAW Simulator Block Diagram

2.3 The Electronic Support Measures (ESM) System

The electronic support measures (ESM) detection domain is limited in range to a maximum of 250 km from the ESM antenna and elevation coverage is from 0° to 40°. A signal-to-noise ratio is calculated based on ESM characteristics such as the frequency, pulse repetition frequency, pulse width, threat transmitting power and range. A simple radio frequency power computation was calculated to determine the signal-to-noise ratio of the received pulses. If the S/N ratio exceeded a threshold, a target was detected. The detection test was performed periodically. The ESM provided bearing and target identification information, and noise was added to the bearing measurements forwarded from the ESM model to the associated tracking processor model. A decision was taken never to update the fused tracks using ESM bearings since scenarios in which the emission control policy (EMCON) would be silent were not considered. Only a limited number of anti-ship missile identities were considered (such as Exocet, AS-6).

2.4 The Infrared Search and Track System (IRST)

The detection domain of the IRST device was limited in range according to the weather conditions and was limited in elevation from 0° to 23°. Under sunny weather conditions, 90% probability of detection can be achieved at a range of 25 km from the IRST system. If the heat energy from a target lay between certain limits (lowest frequency of operation, highest frequency of operation) a simple infrared power computation was made to calculate the signal-to-noise ratio coming from the anti-ship missile threats. The signal-to-noise ratio depended on IRST characteristics, the threat infrared (IR) signature and the range. If the S/N ratio exceeded a threshold, a target was detected. The detection test was periodical with period equal to the IRST system rotation. The IRST system provided bearing and elevation information which were corrupted by suitable noise terms.

2.5 The Surface-to-Air Missile (SAM) Model

The SAM model has been chosen to simulate short range systems requiring semi-active illumination and medium range systems using midcourse guidance. The missile flight profile is explicitly modelled. As soon as the missile is in flight, its position is updated periodically. The modelling of the missile flight profile is required to provide a realistic interception time when dealing with crossing and/or maneuvering targets. The model is based on the assumptions below.

First, the target, the SAM and the fire-control radar antenna are always collinear (i.e., the missile always has enough available lateral acceleration to follow its guidance commands). This type of flight profile will provide a good approximation for the interception time even when dealing with crossing and/or maneuvering targets. The missile is guided towards the "true" threat (i.e., the model assumes that the guidance commands are not corrupted). This assumption is valid since the guidance errors do not significantly influence the interception time. In the case of short range missiles, the missile cannot go out of the continuous wave illumination (CWI) cone because the illumination cone is always wide enough (typical beamwidth = several dozens of degrees) to prevent any loss to the missile, even when prosecuting a crossing and/or maneuvering target. In the case of medium range missiles, there is no modelling of the J radar band uplink used in midcourse guidance. In this case also, it is assumed that the threat, the SAM and the CWI are collinear. Thus, if an intercept is being obtained at medium range and the target maneuvers in the vertical plane, it is assumed that the SAM has a sufficiently high normal acceleration in the vertical plane to intercept the target. In practice this may not always be possible. Thus, the results coming from the AAW simulator may be more optimistic than those observed in SAM trials. Secondly, if and when the SAM gets further from the fire-control radar than the threat, it is said to intercept the threat (because of the collinear condition) and a random number is then drawn and compared with the probability of kill to determine whether or not the threat is destroyed. The required input data for this model are the missile velocity for calculating the range from the ship, the maximum flight time and the probability of kill.

2.6 The Threat Model

In the ASM models developed, radar, anti-radiation and infrared seekers are simulated. The search domain of the radar seeker head is a three dimensional cone with the cone axis equal to the threat heading. A signal-to-noise ratio is calculated for each target in the cone and is a function of the radar characteristics of the seeker head, the target radar cross section, the target range and the power of the jammers. A target is declared to be detectable if the signal-to-noise ratio exceeds a certain threshold. Among the detectable targets, the active radar seeker head locks onto the one with the highest signal-to-noise ratio. The active seeker head modelled here chooses a fixed target and remains locked onto this target even after chaff is deployed. If there is no detection, the search process is repeated periodically. The locked-on seeker head periodically checks to make sure that the target can be detected. If no target is detected after an appropriate time interval, the threat ceases to exist. The navigation law used in the threat model is an approximation to proportional navigation. A threat that is not destroyed by a hardkill weapon always intercepts its target. The probability of kill is assumed to be constant. The anti-radiation missile (ARM) seeker head model will be the same as the active radar seeker head model but there will be a different detection test.

Similarly, the model of the infrared seeker will be the same as the active radar seeker head model but the detection test will depend on the ship's infrared signature. Threats will be equipped with either an infrared seeker or a radar seeker (there will be no dual seeker configurations). The seeker head simulated here is closer to the reticle class of IR seeker heads than the later generation of IR seeker heads which use thermal imaging. Infrared flares will be deployed for the purpose of distracting the IR seeker head. IR flares will be deployed whenever the chaff is deployed and will, therefore, be deployed in the same location and at the same time as the chaff decoy.

2.7 The Chaff and Chaff Controller Models

Only the distraction mode of chaff is simulated against ASM threats. The effect of the wind on the motion of the chaff is modelled; the chaff radar cross section varies with respect to time and the chaff position at the moment of canister detonation depends on the selected launcher. There are four launchers for the chaff system of the AAW simulator : these launchers are set at angles of 45°, 110°, 250°, 315° with respect to the north in the counterclockwise sense. The chaff launcher is selected by the TEWA in order to maximize the radar cross section of the chaff clouds with respect to the incoming ASM and also so that the wind direction blows the clouds away from the ship. In some cases, a small rotation of the ship to change the course may be necessary in order to satisfy both of these conditions in the best possible way. In addition, rotation of the ship is required in order to reduce the radar cross section of the ship with respect to the incoming missile. Therefore, at the moment that chaff is required to be used, the best launcher must be chosen in order to maximize the radar cross section of the chaff clouds with respect to the threatening anti-ship missile, and in order to make sure there is separation between the ship and the chaff clouds and a small rotation and change of course may be necessary to improve these above factors and to reduce the ship's radar cross section to the incoming anti-ship missile. In the AAW simulator, the time delay between the TEWA decision to fire chaff and the canister detonation is assumed to be a constant. In an operational system, this time varies as a function of the chaff fuse time.

2.8 The Naval Gun and Close-In-Weapon System models

Since the naval gun and the close-in-weapon system (CIWS) have similar functionality, they are represented by similar models in the AAW simulator. In both models devised for the AAW simulator, the time from the fire-control radar lock-on to open fire is assumed to be a constant. The time from open fire to intercept is a function of the threat range, threat velocity and ammunition velocity. The region in which both gun systems can fire is limited in range, elevation and has azimuth blind zones. The kill probability is assumed to be a constant. In both the naval gun and CIWS models, there is a combined value representing the kill probability and the probability of interception of the gun/CIWS burst for a non-maneuvering target coming in a straight line to the ship. For both the gun and CIWS, this combined value is equal to 0.7. The naval gun fires a burst of 20 rounds of ammunition at a firing rate of two rounds per second, while the CIWS fires a burst of 300 rounds of ammunition at a firing rate of 30 rounds per second. A destruction test is performed at time equal to the predicted interception time of the first shell. If the destruction test is negative, then the gun engagement is over, there is no destruction of the anti-ship missile and the result is communicated to the result evaluation knowledge base of TEWA. If the destruction test is positive, then the anti-ship missile is removed from the simulation and the result is communicated to the result evaluation knowledge base of TEWA.

2.9 The Tracking Processor

The tracking processor is responsible for track association and management. Perfect contact-to-track association is assumed based on threat identities. In this simple model, the contacts correlate with the tracks if they have the same identifiers as the threats that produced the echoes. Tests are performed to ensure that only one echo correlates with a given track and that only one track correlates with a given echo. A track creation mechanism is provided to initiate new tracks from echoes that were not used to update existing tracks. A track deletion mechanism is provided to delete tracks that have not been updated for a specified period of time. The tracking processor maintains a database of current tracks.

2.10 The Continuous Wave Illuminator

In the CWI model, it is assumed that the CWI, the SAM and the threat always lie in the same straight line and, in addition, the SAM can maneuver in the CWI beam to compensate for any maneuver made by the ASM threat. Once a SAM is fired at an ASM, it always intercepts the threat under CWI. The SAM will or not destroy the threat depending on whether the value of a random deviate is less than or greater than the SAM kill probability. The random deviates are taken from a uniform distribution on [0,1]. If the kill probability is .8 and a random deviate r is drawn satisfying $r \leq .8$, then the target ASM is destroyed by the SAM. If the value drawn $r > .8$, then the target ASM is not destroyed by the SAM.

2.11 The Sensor Data Fusion Processor (SDFP)

The following Kalman filter is being used in order to create fused tracks.

$$\hat{\mathbf{x}}(k/k) = \hat{\mathbf{x}}(k/k-1) + \mathbf{K}(k)[\mathbf{y}(k) - \mathbf{H}\hat{\mathbf{x}}(k/k-1)] \tag{2.1}$$

$$\mathbf{K}(k/k) = \mathbf{P}(k/k-1) + \mathbf{H}^T[\mathbf{HP}(k/k-1)\mathbf{H}^T + \mathbf{R}] \tag{2.2}$$

$$\mathbf{P}(k/k) = [\mathbf{I} - \mathbf{K}(k)\mathbf{H}]\mathbf{P}(k/k-1) \tag{2.3}$$

$$\hat{\mathbf{x}}(k+1/k) = \Phi\hat{\mathbf{x}}(k/k) \tag{2.4}$$

$$\mathbf{P}(k+1/k) = \Phi\mathbf{P}(k/k-1)\Phi^T + \mathbf{Q}(k) \tag{2.5}$$

where :

x = state vector (e.g. range, range rate);
K = Kalman gain;
H = measurement matrix;
P = Kalman filter covariance matrix;
Φ = the state transition matrix;
Q = plant noise covariance matrix;
R = measurement covariance matrix.

Equations 2.4 and 2.5 are the prediction equations. The notation ($k|k$-1) means time k when given time k-1.

2.12 The Fire-Control Processor

The fire-control processor coordinates fire-control radar activities with the gun and missile system. It forwards target designations from the TEWA to the fire-control radar. It triggers the missile system (or gun) upon receipt of lock-on information from the fire-control radar.

2.13 The Missile Launch Controller (MLC)

The missile launch controller model simulates the operations and time delays associated with preparing a missile for launch (loading, warming). There are reversible and irreversible preparation time delays and these are constants. It is assumed that the reversible preparation time delay is less than the irreversible preparation time delay. If the time is after the irreversible preparation time delay a missile is launched independently of events taking place in the environment. If the time is after the reversible preparation time delay but not after the irreversible preparation time delay, the missile launching operation may be cancelled.

2.14 The Jammer

In the model developed for the AAW simulator, the jammer only generates broadband noise. There is a simple noise power computation that is based on the ASM radar characteristics and the missile range from the ship. This calculation indicates the amount of radio frequency noise that must be generated to distract the ASM or break lock. This noise level is introduced into the threat seeker radar equation.

2.15 The Sensor Management Processor

Only the infrastructures for the sensor management processor of the current AAW simulator have been built. In future work, the sensor management processor could be used to simulate the selection of tracking beams for an active phased array radar (APAR).

2.16 The Internal Communication System

The internal communication system allows the various elements of the combat system to communicate with one another within a ship. It is modelled by a simple "switching box". Messages are sent from one combat system module to another with the assumption of no delay, although the computer may take a certain amount of time to send a message, for example, from the long range radar tracking processor node to the sensor data fusion node and then to the TEWA node. The internal communication system models the message traffic in the combat system of a warship.

2.17 The External Communication System

There is a possibility of simulating external communication systems such as LINK 16 or the NILE system in the AAW simulator. Both of these systems are rapid and improved datalink systems with respect to the AAW standpoint, i.e., anti-air warfare radar, ESM and ECM information as well as weapon designation orders can be sent from one ship to another in a time which is compatible with AAW requirements.

2.18 The Force Resource Data Fusion Processor

The force resource data fusion model collates weapon status information and forwards it to the TEWA.

2.19 The Ship Course Model

In the ship platform model, the two dimensional trajectory of the ship in the AAW simulator is defined by entering the initial point, final point and speed of each ship segment. An ordered heading change can be implemented and the rate at which the heading changes is always less than a maximum limit. Once the turn has been implemented in order to make the use of hardkill and/or softkill weapons more effective, the ship continues in a straight line with its new course until another turn is required for the deployment of hardkill and/or softkill weapons.

3.0 THE TEWA MODULE

The knowledge-based TEWA process described in Refs. 1 and 2 ranks air threats and assigns hardkill and softkill weapons to them in the case of a single stationary AAW destroyer attacked by anti-ship missiles. This knowledge-based TEWA, which was known under the name of "TEWA expert system", was tested for correctness of firing decisions by connecting it to an open loop stimulator called the target track generator. This open loop stimulator contained weapon system models such as Surface-to-Air Missiles (SAM) and chaff and it also generated fused tracks coming from radar and ESM sensors.

The improved knowledge-based TEWA of the AAW simulator is an extension of the previous knowledge-based system (TEWA expert system) by the addition of rules to decide on ship rotation before hardkill and/or softkill deployment. This is a closed loop system where the threat trajectories are not calculated in advance. They are calculated as time advances and they can be modified by the deployment of weapons by the ship.

This section will describe both the TEWA expert system and the improved TEWA of the current version of the AAW Simulator.

3.1 The TEWA Expert System

In an open loop system, the trajectories of all anti-ship missile threats are computed in advance from their launch point until they hit the ship. If the knowledge-based TEWA assigns a weapon to a threat, such as chaff, either the operator decides whether it is effective against the threat or there is a probabilistic chaff model in the open loop stimulator based on random numbers that decides whether the countermeasure is effective against the threat. If the outcome is that it is effective against the threat, the anti-ship missile is removed from the simulation and hence the ship's sensors cease generating tracks for the threat. If the outcome is that the countermeasure is not effective against the threat, then it continues to follow its predefined trajectory to the ship. The threat will only reach the ship if all hardkill and softkill weapons used against it fail.

3.1.1 The Knowledge-Based System

The design of the knowledge-based system for the single, stationary AAW destroyer is given in Fig. 2. It consists of four HUMBLE knowledge bases, and a ranking of reactions function. The knowledge bases are called respectively : Target Evaluation, Result Evaluation, Force Resources Evaluation and Candidate Reaction Evaluation.

The ***Target Evaluation knowledge base*** consists of two types of rule sets. These are called low level rules and high level rules. The low level rules concern threat identity, threat radar mode, threat engagement status and threat kinematic parameters. The kinematic rules act on attributes coming from the sensors such as threat velocity and current threat position in order to obtain a quantifier describing the kinematic behaviour of the threat. In actual fact, threat velocity and position are used to calculate the CPA (closest point of approach) and TTGI (time to reach the closest point of approach) and these will classify the kinematic values of the threat into categories such as : "strong kinematics" or "moderate kinematics". The identity rules act on qualifiers such as “exocet”, “AS-6” or “aircraft” to produce an identity. Thus, any sea-skimming missile entered through the AAW simulator user interface receives the qualifier “exocet”, and will cause the “exocet” identity rule to fire and thus sends an identity “exocet” to the high level rules. The other low level rules function in a similar way. The high level rules are rules for combining the threat identity characteristics, the threat kinematic values, the radar mode characteristics and the engagement status characteristics that were derived from the low level rules. They combine the four above characteristics to produce a value of threat level. The value of threat level can vary from one to five depending on whether the threat is considered to be more or less dangerous to the ship. A value of five assigned to a threat indicates that it is very dangerous, while a value of one indicates that it is only slightly dangerous.

There is also a ***Result Evaluation knowledge base*** that does kill assessment for each kind of hardkill and softkill weapon system on the ship. In the original version of the knowledge-based system, either the operator decides whether a threat is destroyed by a weapon, or, this is decided by a random number generator. Immediately, after the decision is made, the sensors of the ship must undertake a kill assessment. A kill assessment model has been implemented for SAM missiles, chaff, the jammer, the medium calibre naval gun and the CIWS. According to this model, a projected time is calculated for the interception time of one of these weapon systems against a threat. If the weapon system destroys the threat and the threat destruction or decoy time occurs within the predicted time interval, the result of kill assessment is that the threat is “killed”. If the weapon system intercepts the threat (i.e., there is a SAM intercept, a gun intercept, a CIWS intercept or chaff clouds are possible candidates for the threat’s seeker head) and the interception time occurs within the predicted interval but the threat is not destroyed or decoyed, the result of kill assessment is “notkilled”. If the threat destruction or decoy time occurs after the predicted time window all ownship SAMs, gun rounds, CIWS rounds are lost and the threat is assessed as "notkilled". If the intercept or destruction time of the threat occurs before the predicted time interval, no kill assessment takes place. This last occurrence has never been observed. The result of kill assessment will affect future threat rankings and hence future situation and threat assessments.

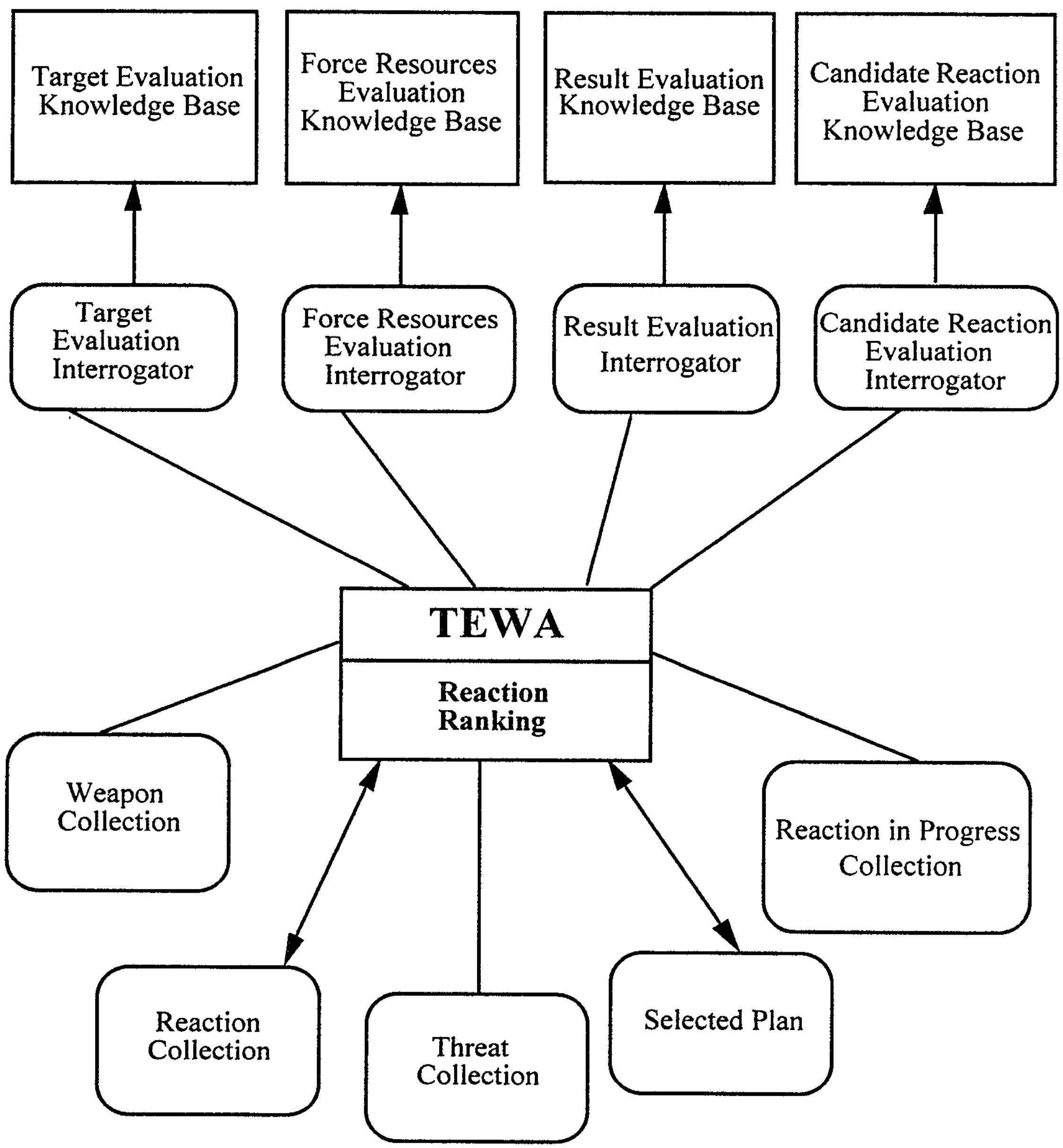

FIGURE 2 - An architecture for the knowledge-based system

There is also a ***Force Resources Evaluation knowledge base*** which monitors the availability, stock level and status of weapon systems before assignment. Obviously, the availability is important since the fire-control radar of a SAM or gun cannot be assigned to another threat if it is already assigned to one. The knowledge base will also keep track of the stock level of missiles and ammunition, because in an air engagement, economic use of weapons has some significance, although it is considerably secondary to the one of ship survivability. The status of weapon systems can be fully operational, degraded or nonoperational. A weapon system is said to be operational if it is available and has a full load of ammunition; it is nonoperational if it is not available or has no ammunition and it is said to be degraded if it is available and has a limited amount of ammunition.

There is a ***Candidate Reaction Evaluation knowledge base*** which assesses whether candidate hardkill or softkill weapons can be assigned to threats. It is divided into two parts. The first part does engageability for each of the hardkill/softkill weapon systems on board the ship and the second part associates predicted effectiveness with each weapon that has passed the engageability test.

3.1.2. The Weapon Allocation

Once each track has passed through the Target Evaluation knowledge base and the Candidate Reaction Evaluation knowledge base, plans must be formed to assign weapons to tracks. A plan is considered to be a complete assignment of weapons to all tracks in the track database. In order to rank these tracks, the following definitions must be made. Let C_{ij} be the confidence that track i is at a threat level of j, let E_{ik} be the effectiveness that the k^{th} weapon assigned to the i^{th} track will destroy or decoy it. C_{ij} is a real number satisfying $-1.0 \leq C_{ij} \leq 1.0$, while E_{ik} is a real number satisfying $0.0 \leq E_{ik} \leq 1.0$. Let Ω_i be the uncertainty associated with determining the threat ranking of the i^{th} track ($-1.0 \leq \Omega_i \leq 1.0$), m be the current threat level ($1 \leq m \leq 5$). Track i in the track database is ranked according to the following sum:

$$r_i = m\Omega_i + \sum_{j=1}^{5} jC_{ij}E_{ik} \tag{3.1}$$

If a plan contains N tracks, the plan is ranked by summing the formula (3.1) over all tracks and dividing by a normalizing factor. The normalizing factor is the sum of all quantities (3.1) for the case in which all N tracks have threat level 5 and all weapon effectiveness E_{ik} are equal to 1. Denote the normalized sum of (3.1) by F. Since, any plan that assigns weapons to $N + 1$ tracks is deemed superior to one that assigns weapons to N tracks, the survivability factor, S_v, associated with a plan is defined as follows:

$$S_v = \frac{F+N}{N_T+1} \tag{3.2}$$

where N is the number of assigned tracks in the plan and N_T is the number of tracks in the track database system.

It is also necessary to include the effect of interference and stock level in the overall formula for ship survivability. In order to do this, it is necessary to introduce two new variables:

$$I_p = \frac{N_B}{N_p} \tag{3.3}$$

$$R_U = \frac{N_C}{N_p} \tag{3.4}$$

where I_p is the impact and R_U, the resource usage. The variables used in equations (3.3) and (3.4) are defined as follows:

N_B = Number of [track(i),weapon(j)] pairs where $E_B = 0$

N_C = Number of [track(i),weapon(j)] pairs where $E_C = 0$

N_p = Total number of [track(i), weapon(j)] pairs

In N_B, N_C, N_p above, the indices i and j range respectively over all tracks in the track database and all weapons on board ship and E_B, E_C are defined below. The Candidate Reaction Evaluation knowledge base considers spatial interference caused by a chaff cloud obscuring a fire-control radar's line of sight. For a given threat ship geometry, a chaff launcher (the selected launcher) is chosen to be the nearest launcher firing chaff downwind of the ship along the threat reciprocal. Spatial interference is declared when the chaff cloud fired from the selected launcher lies between a threat and the ship. Otherwise, there is no interference.

The interference calculations are made taking into consideration that the ship is moving with a certain velocity, that the chaff clouds are moving at the wind speed in the wind direction and the threat has its own velocity. If the chaff clouds which have been deployed obscure any fire-control radar line of sight, an E_B parameter receives the value of 1. Otherwise, if there is no obstruction of the fire-control radar's line of sight E_B is assigned the value of 0. These calculations are made at the moment that the weapon allocation is made. In addition, it often happens that the chaff is launched downwind of the threats so that there is no spatial interference between the fire-control radars and chaff concerning this particular threat. With the assumptions of our models, interference can possibly arrive if the chaff is assigned to a particular threat and a fire-control radar is assigned to another one whose bearing varies a large amount from the first threat. In the case that chaff is launched upwind of the threats, the time at which the chaff passes between the ship and the threat is often of short duration when the chaff relative speed with respect to the ship is large.

In order to keep track of the number of missiles used in the engagement or the amount of ammunition still available to the guns, an E_C variable will receive the value of 1 if the use of the weapon reduces the stock below some critical level. Otherwise, the value of the parameter remains set at 0.

If there is no interference then $E_B = 0$ for all track weapon pairs and the value of impact is 1. In fact, a high value of impact denotes little interference and vice-versa. Similarly, if $E_C = 0$ for all track weapon pairs, i.e., there is no restriction on stock level, then R_U is 1. The higher the value of R_U, the more likely the plan will be chosen since there are no limitations on resource usage. The final function for selecting between plans is given by

$$D_{plan} = 0.8S_v + 0.1I_p + 0.1R_U \tag{3.5}$$

3.2 The Improved TEWA Module

The knowledge-based TEWA system that was developed for a single stationary AAW destroyer and is described in the previous section has been modified in order to accommodate hardkill or softkill reactions deployed from a maneuverable ship. The AAW simulator is being developed for several warships which can maneuver when attacked by anti-ship missiles. Ship rotation is used to support hardkill reactions. More specifically, ship rotation may occur in order to unmask a fire-control radar or naval gun that is in a blind zone.

In order to design a TEWA that supports rotation before hardkill deployment, the following steps were taken. The reactions that were considered unengageable because there were blind zone problems were noted. The amount of rotation required to make each reaction engageable was calculated. An attempt was made to create engageable reactions before considering hardkill reactions that involve rotation. A certain number of penalty points were associated with a plan when a component reaction involved a rotation because of the delay incurred before it could be implemented. Thus, if it is estimated that the ship cannot turn sufficiently fast within the time allotted (i.e., before it is hit by an ASM) then the rotation will not take place.

Whenever a plan P has a constituent reaction R that incorporates a rotation, calculations are made to determine whether other reactions in the same plan which are engageable would be made unengageable as a result of the rotation. Now, consider a plan P = [R1, R2, R3] where R1 is a reaction that involves a rotation while the others do not involve rotation. Further, assume that P has a score of X according to the existing methods of scoring plans. Suppose that it is determined that the implementation of R1 would make R2 unengageable. In such a case, the plan P is modified to be [R1, R3] and a new score is calculated including the previous penalty factor. Consider a plan P = [R1, R2, R3] where R1 and R3 both require rotation. It is always possible that plans may be drawn up (e.g., plan P) that have more than one reaction involving rotation. Clearly, both rotations cannot be implemented. In this case, the rotation is chosen which is associated with the reaction assigned to the highest ranked threat.

With the current TEWA design of the AAW simulator, precedence is given to the implementation of hardkill reactions including those needing rotation over that allocated to the implementation of softkill reactions. This means that the threats of the AAW simulator are considered to be engageable by hardkill weapons first before being engageable by softkill weapons. During the course of the battle, a certain number of threats will become engageable by softkill weapons. These reactions will, in general, require a rotation. With the current implementation of the AAW simulator, a softkill reaction requiring a rotation can be implemented directly after a hardkill reaction requiring a rotation. In this case, the softkill reaction's rotation cancels the former hardkill reaction's rotation and this is noted as a case of interference between hardkill weapons and softkill weapons.

At the present moment, ship rotations are not considered as being irreversible, i.e., when a rotation for a hardkill or softkill reaction is being implemented it may be interrupted by a subsequent rotation. The reason for this is because research is still being done on hardkill/softkill coordination and in the AAW simulator there was only a requirement to find out how many times softkill weapons decoyed threats and how many times they interfered with hardkill weapons. The most general form of softkill reaction which is typical of chaff, jammers and passive decoys is a rotation of the ship to place it in the best position for softkill weapon deployment followed by a change in ship velocity to ensure feasibility of the softkill weapon deployment. After the weapon is deployed, another rotation and change in ship velocity give the ship the best chance to leave the threat-weapon engagement zone without any damage. In the last example given above, i.e., in the plan P consisting of [R1, R2, R3] where both R1 and R3 require rotations, R3 could be a hardkill reaction and R1 could be a softkill reaction. Thus, R3 is assigned to the most highly ranked threat and if the effect of implementing R3 does not prevent the softkill reaction R1 from being implemented, it is also executed by the ship.

4.0 TEWA RESULTS

This section presents the TEWA results and the AAW events from the AAW simulator for a single ship scenario and for a four ship scenario.

4.1 A Single Ship Scenario with Multiple Threats

A single ship scenario in which twelve anti-ship missile threats attack a CPF-like ship from the south, as shown in Fig. 3, was executed using the new sensor, weapon and command and control models of the improved version of the AAW simulator. The ship is heading north at a speed of 25 knots (12.5 m/s). There is a 30 knot (15 m/s) wind coming from the northeast at an angle of 55° (see Fig. 3). The standoff jammer aeroplane is located at a range of 210 km from the CPF seaborne platform at a bearing of 270° measured counterclockwise from the east with respect to the CPF position. The jammer performs noise jamming directed at the CPF throughout the engagement. The following results were obtained and are described in Appendix A (Section A.1). These results contain information about TEWA decisions taken by the single ship and AAW events closely related to these decisions or having an important effect on them. The threats consist of sea-skimmers, shallow divers and high divers. In the scenarios for the improved AAW simulator, a coordinate system is chosen, where 0° corresponds to due east, 90° to due north, clockwise rotations are associated with negative rotation angles and counterclockwise rotations are associated with positive rotation angles (see Fig. 3). The main threat events of this scenario are summarised in Table I below. All times in Table I are indicated in seconds.

4.2 A Multiple Ship Scenario with Multiple Threats

A multiple ship scenario in which eight anti-ship missile threats attack a convoy of four ships consisting of two TRUMP-like ships and two CPF-like ships (see Fig. 4 for a description of the scenario) was executed using the new sensor, weapon and command and control models of the improved AAW simulator. In Fig. 4, it is to be noted that all coordinate positions are given in metres. In this scenario, there is no wind and there are no standoff air jammers. The four ships are heading north at a speed of 12.5 m/s (25 knots). The following results were obtained and are described in Appendix A (Section A.2). These results contain information about TEWA decisions taken by the four ships of the scenario against the attacking air threats and AAW events closely related to these decisions or having an important effect on them. All threats are sea-skimmers, except threats 7 and 8 which are surface-to-surface anti-ship missiles. As in the case of Fig. 3, a coordinate system is chosen in Fig. 4, where 0° corresponds to due east, 90° to due north, ship rotations in the clockwise sense are indicated by negative rotation angles while ship rotations in the counterclockwise sense are indicated by positive rotation angles. The main threat events are summarised in Table II below. All times in the table are given in seconds.

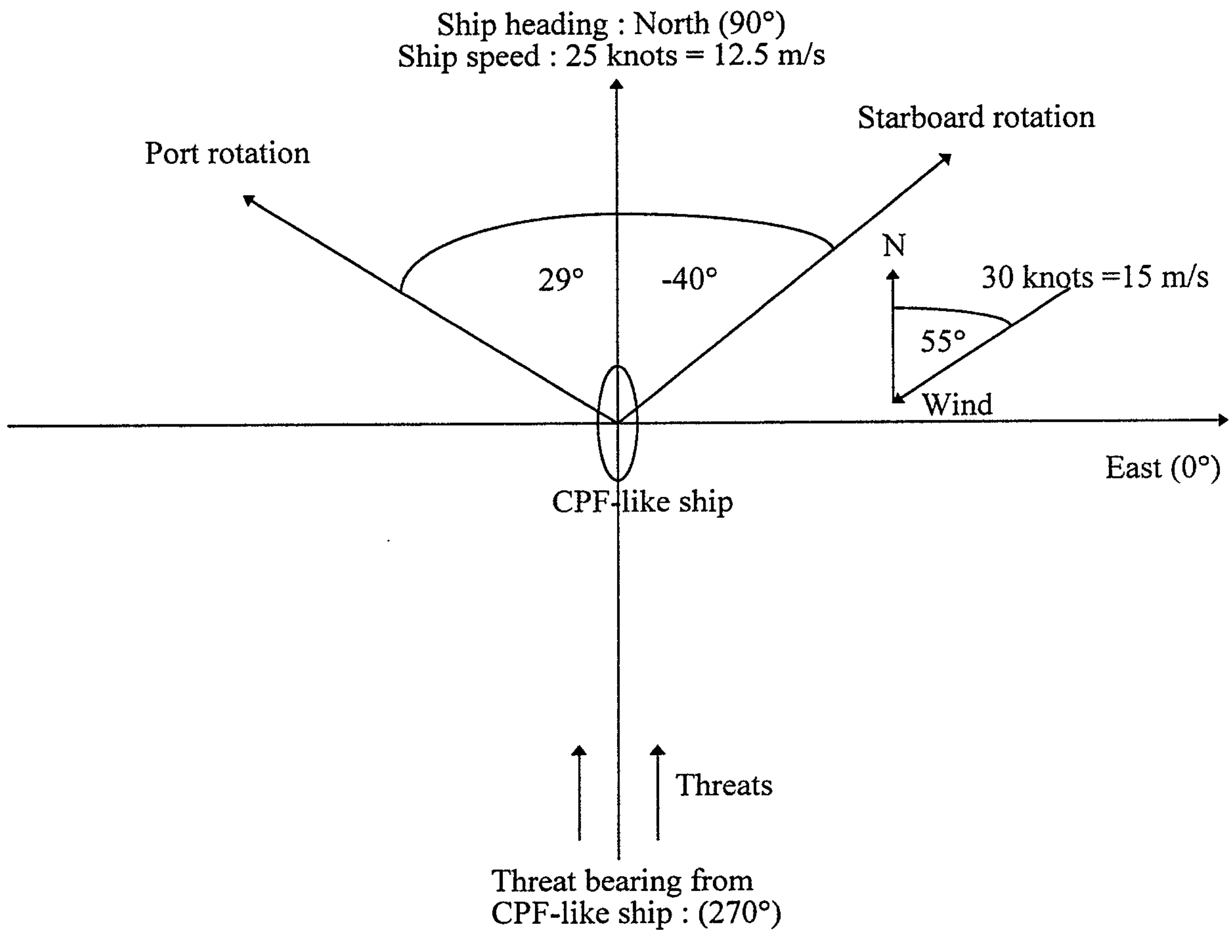

FIGURE 3 - Coordinate system used in the single ship scenario for the improved AAW simulator

TABLE I

Threat events of the single ship scenario

Threat	Launch Time (sec)	Seeker Activation	Lock-On Time (sec)	Lock On Target (sec)	Destruction Time (sec)	Notes
1.	696.31				970	Destroyed by missile 1
2.	673.22	954.55	957.55	CPF chaff cloud 1	979	Destroyed by missile 3
3.	659.79	954.56	957.56	CPF radar	991	Destroyed by missile 5
4.	721.31	1002.1	1005.1	CPF	1014	Destroyed by missile 9
5.	698.22	979.55	982.55	CPF chaff cloud 2	1026.5	Decoyed - flies through chaff cloud
6.	684.79	979.56	982.56	CPF radar	1024	Destroyed by CIWS burst 1
7.	726.31	1007.1	1010.1	CPF	1026	Destroyed by gun burst 1
8.	703.22	984.55	987.55	CPF jammer (HOJ) mode	990.55	Decoyed - jammer is turned off
9.	689.79	984.56	987.56	CPF radar	1026	Destroyed by missile 11
10.	751.31	1032.1	1035.1	CPF chaff cloud 4	1043	Destroyed by gun burst 2
11.	728.22	1009.5	1012.5	CPF chaff cloud 3	1054	Destroyed by missile 15
12.	714.79	1009.6	1012.6	CPF chaff cloud 3	1056.6	Decoyed - flies through chaff cloud

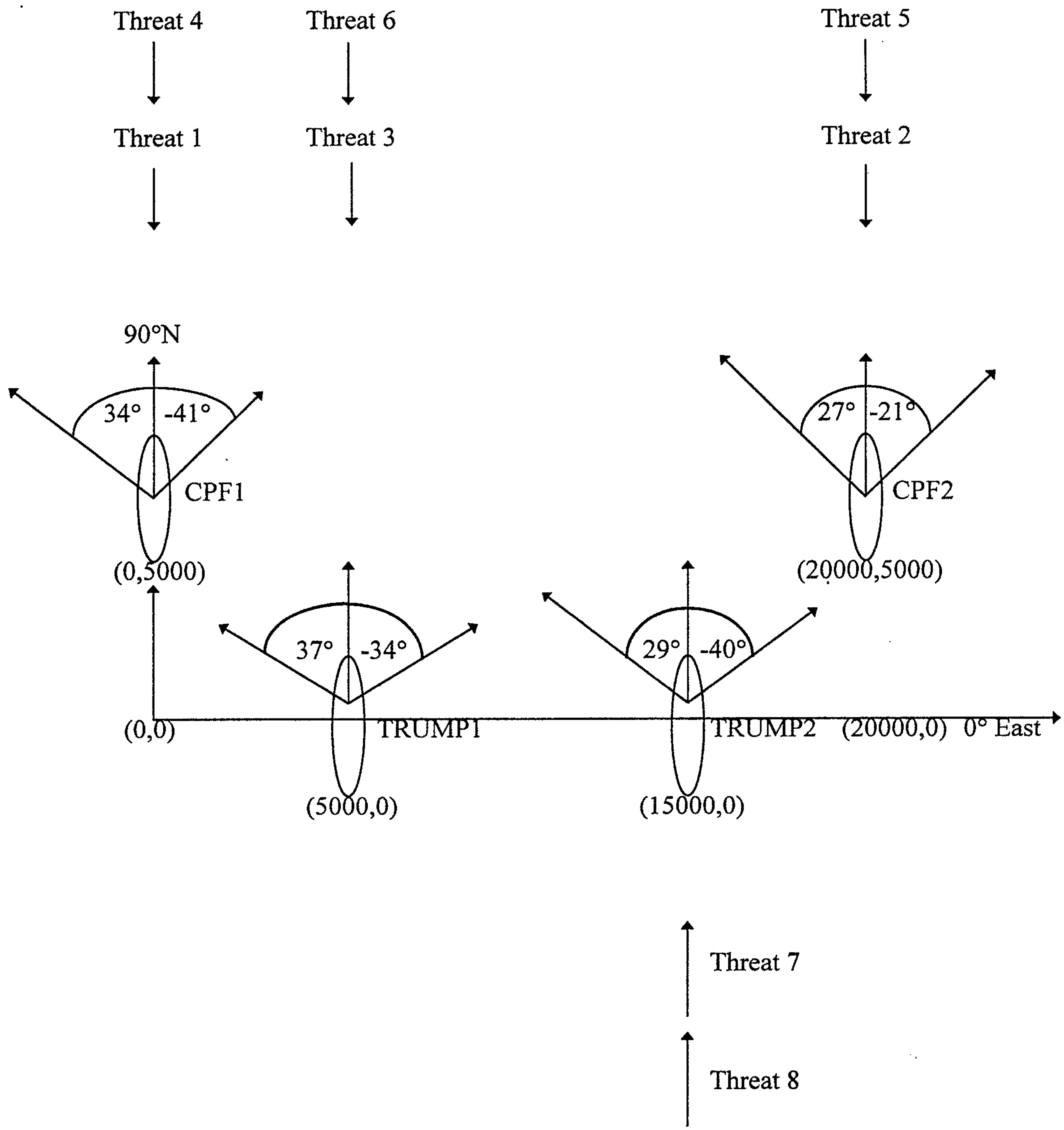

FIGURE 4 - Multiple ship scenario for the improved AAW simulator

TABLE II

Threat events of the multiple ship scenario

Threat	Launch Time(s)	Seeker Activation	Lock On Time(s)	Lock On Target	Destruction Time(sec)	Notes
1	196.31	477.13	480.13	CPF1 Radar	495	Destroyed by CPF1 Missile11
2	196.31	477.13			478	Destroyed by CPF2 Missile2 Missile1 missed
3	196.31				443	Destroyed by TRUMP1 Missile3
4	201.31	482.13	485.13	CPF1 Radar	502	Destroyed by CPF1 Missile13
5	201.31	482.13	485.13	CPF2	497	Destroyed by CPF2 Missile5
6	201.31				478	Destroyed by CPF1 Missile3
7	262.14				434	Destroyed by TRUMP1 Missile1
8	272.14	461.85	464.85	TRUMP2 Chaff Cloud2	482	Destroyed by TRUMP1 Missile5

4.3 Discussion of the results obtained from the AAW simulator

An analysis of the results presented in Tables I and II and in Appendix A shows some interesting issues involved in the assignment of hardkill and softkill weapons to anti-ship missile threats. In the single ship scenario, the knowledge-based TEWA often made a recommendation to rotate the ship in order to deploy hardkill weapons against the threats in the best possible way, i.e., a ship rotation was made so that two fire-control channels could engage the threats instead of one. Later as the threats advanced towards the ship, it was found that distraction chaff could be used. The presence of many threats attacking the single ship made the use of distraction chaff necessary and since the reaction requires a rotation to be effective, a chaff rotation was executed after the hardkill rotation. In this scenario, it was noted that the chaff rotations were often in the port direction, while the rotations for launching surface-to-air missiles were often in the starboard direction. Thus, it was sometimes possible to carry out the first hardkill rotation, fire missiles at the threats and complete the reaction with a successful kill assessment before carrying out a rotation for deployment of softkill weapons. At other times, the first hardkill reaction was not completed before the softkill reaction started and hence the subsequent softkill reaction interfered with the hardkill reaction.

In a frigate or destroyer, doctrine dictates the overall sequence of rotations that the ship makes before deploying specific chaff systems. The AAW simulator does not have doctrine stored in its knowledge bases, yet it can be used to study the TEWA decisions and factors causing interference between hardkill and softkill weapons.

In the multiple ship scenario, at least two ships found it necessary to rotate in the starboard direction in order to use all fire-control radars against the anti-ship missile threats and then subsequently found it necessary to rotate in the opposite direction to use distraction chaff. Thus, this kind of interference also appears in the four ship scenario. However, the author has set up other single ship and multiple ship scenarios where the hardkill and softkill rotation requirements are in the same direction and of similar magnitudes. In this case, there is an absence of interference. Thus for a ship with a combat system specified by the user, and for a given scenario, the AAW simulator will show whether interference occurs between hardkill and softkill weapons.

In the results from the four ship scenario, CPF1 launches fourteen surface-to-air missiles at air threats, CPF2 launches six surface-to-air missiles at air threats, TRUMP1 launches eighteen surface-to-air missiles at air threats and TRUMP2 launches twelve surface-to-air missiles at air threats. In this scenario, the TEWA knowledge-based system of each ship acted independently in order to defend each ship in the best way possible and as a result all eight anti-ship missiles targeted at the four warships were destroyed. Thus, none of the warships were hit by anti-ship missiles which is a positive comment that can be made concerning four independent knowledge-based TEWAs in four different ships.

In several cases in these scenarios, the surface-to-air missiles from three different ships (six surface-to-air missiles altogether) were aimed at the same anti-ship missile threat. In most cases, the first surface-to-air missile reaching the threat destroyed it. In one case, the first two surface-to-air missiles fired at the threat did not destroy it and the threat was destroyed by the third anti-ship missile fired at it. The fifth and sixth anti-ship missiles fired at the threat never destroyed it because it had already been destroyed by another surface-to-air missile.

Although statistical results are not available at the present time concerning weapon assignment of surface-to-air missiles by multiple ships, it could be useful to limit the total number of SAMs used against the same threat. If the weapon assignments of each warship and the threats which the ship is engaging were broadcast over datalink to the other ships as they are in operational Canadian ships, it would be possible to devise a weapon assignment policy for the force where the kill probability of anti-ship missile destruction by SAMs is high but never more than a certain number of surface-to-air missiles are used against the same threat. The anti-air warfare simulator is a tool where weapon assignment policies for multiple platforms can be tested to see which one gives the convoy the best protection, i.e., it can be used to find a weapon assignment policy where the number of ships hit by anti-ship missiles is a minimum while the number of surface-to-air missiles used against these threats is also a minimum.

In the results obtained from the improved AAW simulator for a scenario in which two TRUMP-like ships defending a merchant ship were attacked by fourteen anti-ship missiles, it was observed that jamming from airborne jammers and interference between hardkill and softkill reactions were also important factors resulting in the destruction of ships. In the four ship scenario, airborne jamming was not present and all anti-ship missile threats were destroyed by surface-to-air missiles. In fact, in the four ship scenario, interference between hardkill and softkill weapons resulted in anti-ship missile destruction at very short ranges. If there were no interference, it might have been possible to obtain an intercept at longer range.

In the single ship scenario presented in this section, airborne jamming was present and although the single CPF-like was not hit, three threats were destroyed at the last moment by the naval gun and the CIWS. Statistical testing is required to measure the extent to which airborne jamming and hardkill/softkill interference reduce the air defence capability of warships. In addition in the four ship scenario, it was observed that overkill resulted in a waste of surface-to-air missiles. Statistical tests will have to be conducted to determine whether overkill suppression will result in anti-ship missile intercepts at further ranges from the ship.

5.0 CONCLUSIONS

This memorandum summarises research that has taken place over the last three years in the development of an anti-air warfare (AAW) simulator at Defence Research Establishment Valcartier and at its contractor's site. Initial efforts to study the use of knowledge-based systems for the threat evaluation and weapon assignment process of a stationary anti-air warfare destroyer have lead to the development of algorithms for rotating the ship before deployment of hardkill and softkill weapons. The additional rules were written in SMALLTALK and added to the SMALLTALK/HUMBLE knowledge bases.

The TEWA results obtained from a single ship, multiple threat scenario (one ship attacked by twelve threats) and a multiple ship, multiple threat scenario (four warships attacked by eight threats) are also described in this document. Although the AAW simulator contains no doctrine, it can be used to study various aspects of anti-air warfare such as the interference existing between hardkill and softkill weapons, the use of datalink to reduce overkill, and weapon assignment policies from multiple platforms. These problems have already become evident from the results of the single ship and four ship scenarios. After doing executions using the AAW simulator, the anti-air warfare analyst will become further aware of the problems and interactions arising from the defence of a convoy of warships from air threats.

The closed loop anti-air warfare simulator has the distinguishing feature that the threat evaluation and weapon assignment process in each warship is modelled by a knowledge-based system. Additional rules deciding whether to rotate the ship before hardkill deployment and the amounts of softkill rotation required before and after softkill deployment are described. The descriptions of scenarios where twelve threats attack a single ship and a scenario where eight threats attack four ships have been presented and the results from each of these scenarios are described along with a discussion of their impact on threat evaluation and weapon assignment in the multiple threat, multiple ship problem. These results are considered to be consistent with the design specifications of the new modelled entities for the sensor, weapon and command and control models of the AAW simulator.

6.0 REFERENCES

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APPENDIX A

THE AAW EVENTS OF THE SIMULATION

The AAW events of the simulation for the two scenarios considered in chapter 4 are summarised below.

A.1 A Single Ship Scenario with Multiple Threats

1. At t = 924 seconds, the CPF-like ship cannot engage the predicted interception point for threat 2 using STIR B and the surface-to-air missile system.
2. At t = 924 seconds, the CPF-like ship makes a 40° turn to starboard (clockwise) so that STIR A can engage threat 1. The initial heading is 90°. The threat bearing is 270°.
3. At t = 927 seconds, the CPF-like ship launches a salvo of missiles at threat 1 using STIR B. The missile launching order is confirmed at t = 929 seconds, a kill assessment is made at 973 seconds and the result of kill assessment is that threat 1 is destroyed. The reaction is halted at t = 973 seconds.
4. At t = 933 seconds, the CPF-like ship turns 14° to port (counterclockwise) in order to deploy chaff against threat 1. The turn should end with the ship heading at 80°. It actually ends at 75° because of a subsequent reaction involving a rotation (see item 6). A chaff round is fired from the 110° launcher. A softkill assessment is done at t = 973 seconds and the result is a failure because threat 1 was destroyed by a surface-to-air missile.
5. At t = 935 seconds, the CPF-like ship cannot lock STIR A of the SAM system onto threat 3 because this threat has flown into a blind zone caused by the previous chaff rotation at t = 933 seconds. The reaction is halted at t = 940 seconds. This is an example where the implementation of a hardkill reaction can interfere with a softkill reaction that is already under way.
6. At t = 941 seconds, the CPF-like ship turns 25° to starboard so that it will be able to engage threat 2 with the missile system and STIR A. The initial ship heading is 75°, while the threat bearing is 270°.
7. At t = 946 seconds, the CPF-like ship launches a salvo of surface-to-air missiles at threat 2 using STIR A. The missile launching order is confirmed at t = 948 seconds, a kill assessment is made at 982 seconds and the result of kill assessment is that threat 2 is destroyed. The reaction is halted at t = 982 seconds.

8. At t = 955 seconds, the CPF-like ship uses the jammer against threat 3. Softkill assessment takes place at t = 964 seconds and the result of this assessment is that the threat is "not killed".
9. At t = 974 seconds, the CPF-like ship launches a salvo of surface-to-air missiles at threat 3 using STIR B. The missile launching order is confirmed at t = 978 s, a kill assessment is made at 994 seconds and the result of kill assessment is that threat 3 is destroyed. The reaction is halted at t = 994 seconds.
10. At t = 974 seconds, the CPF-like ship turns 29° to port (counterclockwise) in order to deploy chaff against threat 6. The turn should end with the ship heading at 79°. It actually ends at 79°. Chaff cloud 2 is fired from the 110° launcher. A softkill assessment is done at t = 999 seconds and the result is a failure because threat 6 was an anti-radiation missile.
11. At t = 980 seconds, the CPF-like ship uses the jammer against threat 5. Softkill assessment takes place at t = 989 seconds and the result of this assessment is that the threat is "not killed". The reaction is halted at t = 989 seconds.
12. At t = 986 seconds, the CPF-like ship turns 30° to starboard (clockwise) so that it will be able to engage threat 4 with the missile system and STIR A. The initial ship heading is 79°, while the threat bearing is 269°.
13. At t = 992 seconds, the CPF-like ship engages threat 3 with the CIWS radar and the CIWS. The reaction is halted at t = 994 seconds because threat 3 is destroyed by a surface-to-air missile at t = 994 seconds (see item 9).
14. At t = 993 seconds, the CPF-like ship launches a salvo of surface-to-air missiles at threat 9 using STIR A. The missile launching order is confirmed at t = 995 seconds. The reaction is halted at t = 1009 seconds because STIR A loses track of threat 9, when it enters the STIR A blind zone caused by the rotation of a subsequent reaction (see Item 16).
15. At t = 996 seconds, the CPF like ship launches a salvo of surface-to-air missiles at threat 4 using STIR B. The missile launching order is confirmed at t = 998 seconds, a kill assessment is made at 1017 seconds and the result of kill assessment is that threat 4 is destroyed. The reaction is halted at t = 1017 seconds.
16. At t = 1000 seconds, the CPF-like ship turns 26° to port (counterclockwise) in order to deploy chaff against threat 5. The turn should end with the ship heading at 75°. It actually ends at 76°. Chaff cloud 3 is fired from the 110° launcher. A softkill assessment is done at t = 999 seconds and the result is a failure because threat 5 was already locked-on to CPF chaff cloud 2 (see Table I).

17. At t = 1011 seconds, the CPF-like ship turns 28° to starboard (clockwise) in order to track threat 6 with STIR A. The ship's heading is 76° and the threat bearing is 268°.

18. At t = 1013 seconds, the CIWS radar of the CPF-like ship is tracking threat 6 but cannot engage it yet.

19. At t = 1017 seconds, the CIWS is assigned to threat 6. The designate fire order is confirmed at t = 1022 seconds and the CIWS fires a burst at threat 6. The reaction is halted at t = 1024 seconds and the result of kill assessment is that threat 6 is destroyed.

20. At t = 1017 seconds, the CPF-like ship launches a salvo of surface-to-air missiles at threat 9 using STIR A. The missile launching order is confirmed at t = 1019 s, a kill assessment is made at 1029 seconds and the result of kill assessment is that threat 9 is destroyed. The reaction is halted at t = 1029 seconds.

21. At t = 1019 seconds, the CPF-like ship assigns the naval gun to threat 7 and tracks this target using STIR B. The designate gun order is confirmed at t = 1021 seconds, a kill assessment is made at 1028 seconds and the result of kill assessment is that threat 7 is destroyed by gun burst 1. The reaction is halted at t = 1028 seconds.

22. At t = 1025 seconds, the CIWS radar loses track of threat 7 because it is destroyed. This CIWS reaction is halted at t = 1027 seconds.

23. At t = 1026 seconds, the CPF-like ship turns 24° to port in order to deploy chaff against threat 12. The turn should end with the ship heading at 72°. It actually ends with the ship's heading at 73°. Chaff cloud 4 is launched from the 110° launcher and the result of kill assessment at t = 1051 seconds is that the chaff cloud is ineffectual because threat 12 is already locked-onto CPF chaff cloud 3.

24. At t = 1029 seconds, the CPF-like ship tracks threat 10 with its STIR B fire-control radar. The missile system and fire-control radar designations to threat 10 occur at t = 1029 seconds and these orders are confirmed at t = 1031 seconds. Missiles are launched at the threat, but STIR B loses track of threat 10 because it is destroyed by a gun burst fired at t = 1043 seconds. The reaction is halted at t = 1044 seconds.

25. At t = 1030 seconds, the gun and STIR A is assigned to threat 10. The gun and STIR A designation is confirmed at t = 1032 seconds, firing begins and target 10 is destroyed by gun burst 2. The reaction is halted at t = 1043 seconds.

26. At t = 1037 seconds, the CPF-like ship rotates 32° to starboard so that STIR A can track threat 11. The initial heading of the ship is 73° and the bearing of threat 11 is 261°.

27. At t = 1044 seconds, the CPF-like ship launches a salvo of surface-to-air missiles at threat 11 using STIR A. The missile launching order is confirmed at t = 1047 seconds,

a kill assessment is made at 1058 seconds and the result of kill assessment is that threat 11 is destroyed. The reaction is halted at t = 1058 seconds.

28. At t = 1047 seconds, the CIWS fire-control radar drops the track for threat 10.

29. At t = 1049 seconds, the CPF-like ship rotates 20° to starboard so that STIR A can track threat 11. The current ship heading is 41° and the bearing of threat 11 is 241°.

30. At t = 1052 seconds, the CPF-like ship rotates 21° to starboard so that chaff can be deployed against threat 12. At the end of the turn, the current ship heading should be 11°. Chaff cloud 5 is launched from the 110° launcher. The reaction is halted at t = 1061 seconds when the fused track for threat 12 is dropped from the track database because the threat flew through a chaff cloud.

A.2 A Multiple Ship Scenario with Multiple Threats

1. At t = 342 seconds, TRUMP2 begins a rotation of 40° to starboard so that its STIR A can track threat 7. The initial heading of TRUMP2 is 90° and the initial threat bearing is 270° with respect to the east.
2. At t = 342 seconds, TRUMP2 assigns STIR B and the surface-to-air missile system to threat 7. Unfortunately, STIR B is unable to lock onto the target because of a low signal-to-noise ratio. The reaction is halted at t = 348 seconds.
3. At t = 343 seconds, TRUMP1 begins a rotation of 34° to starboard so that its STIR A can track threat 7. The initial heading of TRUMP1 is 90° and the initial threat bearing is 276° with respect to the east.
4. At t = 343 seconds, STIR B of TRUMP1 and its surface-to-air missile system are assigned to threat 7. The reaction is confirmed at t = 349 seconds, two surface-to-air missiles (missiles 1 and 2) are launched at threat 7, kill assessment takes place at t = 437 seconds, the result is that threat 7 is killed and the reaction is halted at t = 437 seconds.
5. At t = 349 seconds, STIR B of TRUMP2 has also launched two surface-to-air missiles (missiles 1 and 2) at threat 7. The reaction is confirmed at t = 351 seconds and is halted at t = 435 seconds because threat 7 is destroyed by missile 1 of TRUMP1.
6. At t = 352 seconds, STIR A of TRUMP1 and its surface-to-air missile system is assigned to threat 3. The reaction is halted at t = 358 seconds because a low signal-to-noise ratio prevents STIR A from being able to lock onto the threat.
7. At t = 353 seconds, STIR A of TRUMP2 and its surface-to-air missile system is assigned to threat 3. The reaction is confirmed at t = 359 seconds and missiles 3 and 4 are fired from TRUMP2 at threat 3. The threat is intercepted but not destroyed by missile 3, then STIR A loses track of threat 3 because it is destroyed by missile 3 fired from TRUMP1.
8. At t = 359 seconds, STIR A of TRUMP1 and its surface-to-air missile system is assigned to threat 3. The reaction is confirmed at t = 361 seconds and missiles 3 and 4 of TRUMP1 are fired at threat 3. Kill assessment takes place at t = 446 seconds and the result of the kill assessment is that threat 3 is destroyed by missile 3 of TRUMP1. The reaction is halted at t = 446 seconds.
9. At t = 420 seconds, CPF1 rotates 34° to port to be able to engage threat 3 with STIR B. Before the turn CPF1 was heading due north and the threat bearing with respect to the ship was 86°.

10. At t = 420 seconds, CPF1 assigns STIR A and the surface-to-air missile system to threat 3. The reaction is halted at t = 422 seconds because the missile cannot engage the predicted interception point.
11. At t = 425 seconds, CPF1 assigns STIR A and the surface-to-air missile system to threat 6. The reaction is halted at t = 427 seconds because the missile cannot engage the predicted interception point.
12. At t = 427 seconds, CPF2 rotates 21° to starboard so that STIR B can engage threat 3. Before the turn, CPF2 was heading due north. The threat bearing with respect to CPF2 before the turn was 109°.
13. At t = 427 seconds, CPF2 assigns STIR A and the surface-to-air missile system to threat 2. The reaction is halted at t = 429 seconds because STIR A cannot engage the threat.
14. At t = 428 seconds, CPF1 assigns STIR A and the surface-to-air missile system to threat 3. The reaction is confirmed at t = 430 seconds and missiles 1 and 2 are fired at threat 3. However, threat 3 is destroyed by missile 3 of TRUMP1. Consequently, STIR A loses track of threat 3 at t = 444 seconds.
15. At t = 429 seconds, CPF1 rotates 41° to starboard and deploys chaff against threat 3. The turn should end with the ship heading at 73°. It actually ends at 79°. Chaff cloud 1 is fired from the 45° launcher. The fused track is dropped at t = 448 seconds when the threat is destroyed by missile 3 of TRUMP1.
16. At t = 430 seconds, CPF2 assigns STIR A and the surface-to-air missile system to threat 3. The reaction is halted at t = 432 seconds because STIR A cannot engage threat 3.
17. At t = 430 seconds, TRUMP2 begins to rotate 29° to port. The turn should end with the ship heading at 79°. Chaff cloud 1 is launched from the 110° launcher against threat 7. The fused track is dropped at t = 439 seconds since threat 7 is destroyed by missile 1 of TRUMP1.
18. At t = 431 seconds, CPF1 attempts to engage threat 1 using STIR B and the surface-to-air missile system. The reaction is halted at t = 433 seconds because threat 1 is in the STIR B blind zone caused by the chaff rotation to a new course of 79° (see reaction 15).
19. At t = 432 seconds, TRUMP1 begins to rotate 37° to port. The turn should end with the ship heading at 93°. Chaff cloud 1 is launched from the 110° launcher against threat 7. The reaction is halted at t = 437 seconds because threat 7 is killed by an ownship missile.

20. At t = 433 seconds, CPF2 begins to rotate 27° to port. Chaff cloud 1 is deployed from the 110° launcher against threat 3. The turn should end with the ship heading at 101°. It actually ends at 95°. The reaction is halted at t = 447 seconds because threat 3 is destroyed by missile 1 of TRUMP1.
21. At t = 433 seconds, CPF2 assigns STIR A and the surface-to-air missile system to threat 6. The reaction is halted at t = 435 seconds because the SAM system cannot engage threat 6.
22. At t = 434 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 6. The reaction is halted at t = 436 seconds, because threat 6 is in the blind zone of STIR B caused by the chaff rotation to a new course of 79° (see reaction 15).
23. At t = 435 seconds, TRUMP2 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is confirmed at t = 438 seconds. Missiles 5 and 6 are launched at threat 8. The threat is deceived by ownship chaff at t = 465 seconds (see reaction 28). This positive kill assessment means that threat 8 is no longer dangerous to TRUMP2. Hence reaction 23 is halted at t = 465 seconds and missiles 5 and 6 of TRUMP2 are lost.
24. At t = 436 seconds, CPF2 assigns STIR B and the surface-to-air missile system to threat 7. The reaction is halted at t = 438 seconds because the threat is destroyed by missile 1 of TRUMP1.
25. At t = 438 seconds, TRUMP1 begins to turn 12° to port and launches chaff cloud 2 from the 110° launcher at threat 3. The turn should end with a ship heading of 81°. It actually ends at 86°. The reaction is halted at t = 446 seconds because threat 3 is destroyed by an ownship missile.
26. At t = 438 seconds, TRUMP1 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is confirmed at t = 441 seconds. Missiles 5 and 6 are launched at threat 8. Kill assessment takes place at t = 485 seconds and the result of kill assessment is that threat 8 is destroyed by missile 5 of TRUMP1. The reaction is halted at t = 485 seconds. Although from reaction 23, threat 8 is no longer a threat to TRUMP2, it is still considered a threat to TRUMP1.
27. At t = 439 seconds, CPF2 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is halted at t = 441 seconds because the surface-to-air missile cannot engage the predicted interception point.
28. At t = 440 seconds, TRUMP2 rotates 5° to port. The turn should end with the ship heading at 79°. It actually ends at 84°. Chaff cloud 2 is launched from the 110° launcher at threat 8. Kill assessment occurs at t = 465 seconds. The result of kill assessment is that threat 8 is deceived.

29. At t = 442 seconds, CPF2 assigns STIR A and the surface-to-air missile system to threat 2. The reaction is confirmed at t = 444 seconds. Missiles 1 and 2 are launched at threat 2. Kill assessment takes place at t = 481 seconds and the result of kill assessment is that threat 2 is destroyed by missile 2 of CPF2. The reaction is halted at t = 481 seconds.

30. At t = 444 seconds, CPF1 assigns STIR A and the surface-to-air missile system to threat 6. The reaction is confirmed at t = 446 seconds. Missiles 3 and 4 are launched at threat 6. Kill assessment takes place at t = 481 seconds and the result of kill assessment is that threat 6 is destroyed by missile 3 of CPF1. The reaction is halted at t = 481 seconds.

31. At t = 444 seconds, TRUMP2 assigns STIR A and the surface-to-air missile system to threat 2. The reaction is confirmed at t = 446 seconds. Missiles 7 and 8 are launched at threat 2. STIR A loses track because the threat drops under the radar horizon. The reaction is halted at t = 464 seconds.

32. At t = 445 seconds, CPF2 rotates 35° to port so that STIR B can engage threat 5. The initial heading of the ship is 95° or 5° west of due north. The threat bearing is 90°.

33. At t = 446 seconds, CPF2 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is confirmed at t = 448 seconds. Missiles 3 and 4 are launched at threat 8. STIR B loses track because the threat is destroyed by missile 5 of TRUMP1. The reaction is halted at t = 483 seconds which is approximately the time that missile 5 destroys threat 8.

34. At t = 447 seconds, CPF1 rotates 29° to starboard to engage threat 1 with STIR B. The initial heading of the ship is 79° and the threat bearing is 90° (due north).

35. At t = 447 seconds, TRUMP1 rotates 2° to starboard. The turn should end with a ship heading at 88°. In fact it ends with a ship heading at 88°. Chaff cloud 3 is fired from the 110° launcher against threat 1. The result of kill assessment is that threat 1 is not deceived by the chaff cloud. The kill assessment ends at t = 472 seconds and the reaction is halted at this time.

36. At t = 447 seconds, TRUMP1 assigns STIR A and the surface-to-air missile system to threat 2. The reaction is confirmed at t = 449 seconds. Missiles 7 and 8 are launched at threat 2. STIR A loses track because the threat drops under the radar horizon. The reaction is halted at t = 463 seconds.

37. At t = 448 seconds, CPF2 rotates 1° to port. The turn should end with the ship heading at 104°. It actually ends at 109° because reaction 32 has not been completed yet. Chaff cloud 2 is launched from the 110° launcher at threat 6. The fused track is

dropped at t = 482 seconds because threat 6 is destroyed by missile 3 of CPF1 (reaction 30). The reaction is halted at t = 482 seconds.

38. At t = 449 seconds, CPF1 rotates 7° to port. The turn should end with the ship heading at 80°. It actually ends at 75°. Chaff cloud 2 is launched from the 110° launcher. The result from kill assessment is that threat 1 was not deceived by the chaff. Kill assessment takes place at t = 474 seconds and the reaction is halted at t = 474 seconds.

39. At t = 450 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is halted at t = 453 seconds because the surface-to-air missile cannot engage the predicted interception point.

40. At t = 454 seconds, CPF1 rotates 23° to port so that it can assign STIR B and the surface-to-air missile system to threat 2. The initial heading of CPF1 is 75° and the threat bearing is 57°.

41. At t = 458 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 2. The reaction is confirmed at t = 460 seconds. Missiles 5 and 6 are launched at threat 2. STIR B loses track because the threat drops under its radar horizon. The reaction is halted at t = 463 seconds.

42. At t = 462 seconds, CPF2 assigns the jammer against threat 8. Kill assessment begins at t = 471 seconds. The result of kill assessment is that the jammer did not deceive threat 8.

43. At t = 462 seconds, CPF1 assigns the jammer against threat 8. Kill assessment begins at t = 471 seconds. The result of kill assessment is that the jammer did not deceive threat 8.

44. At t = 463 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 5. The reaction is confirmed at t = 465 seconds. Missiles 7 and 8 are launched at threat 5. STIR B loses track because the threat drops under its radar horizon. The reaction is halted at t = 468 seconds.

45. At t = 463 seconds, TRUMP1 assigns STIR A and the surface-to-air missile system to threat 5. The reaction is confirmed at t = 465 seconds. Missiles 9 and 10 are launched at threat 5. STIR A loses track because the threat drops under its radar horizon. The reaction is halted at t = 468 seconds.

46. At t = 463 seconds, TRUMP1 assigns the jammer against threat 8. Kill assessment begins at t = 472 seconds. The result of kill assessment is that the jammer did not deceive threat 8.

47. At t = 464 seconds, TRUMP2 assigns STIR A and the surface-to-air missile system to threat 5. The reaction is confirmed at t = 466 seconds. Missiles 9 and 10 are launched

at threat 5. STIR A loses track because the threat drops under its radar horizon. The reaction is halted at t = 469 seconds.

48. At t = 466 seconds, TRUMP2 rotates 18° to port. The turn should end with a ship heading at 102°. It does actually end at 102°. Chaff cloud 3 is launched from the 110° launcher against threat 6. The fused track is dropped at t = 482 seconds because threat 6 is destroyed by missile 3 of CPF1. The reaction is halted at t = 482 seconds.

49. At t = 467 seconds, TRUMP2 assigns STIR B and the surface-to-air missile system to threat 4. The reaction is halted at t = 472 seconds because the threat drops under the radar horizon of STIR B.

50. At t = 468 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 2. The reaction is halted at t = 470 seconds because the surface-to-air missile cannot engage the predicted interception point.

51. At t = 468 seconds, TRUMP1 assigns STIR A and the surface-to-air missile system to threat 6. The reaction is confirmed at t = 470 seconds. Missiles 11 and 12 are launched at threat 6. STIR A loses track because threat 6 is destroyed by missile 3 of CPF1. The reaction is halted at t = 479 seconds.

52. At t = 469 seconds, TRUMP2 assigns STIR A and the gun system to threat 2. The reaction is confirmed at t = 471 seconds. Gun burst 1 is fired at threat 2. STIR A loses track because threat 2 is destroyed by missile 2 of CPF2. The reaction is halted at t = 479 seconds.

53. At t = 471 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is confirmed at t = 474 seconds. Missiles 9 and 10 are launched at threat 8. STIR B loses track because threat 8 is destroyed by missile 5 of TRUMP1. The reaction is halted at t = 483 seconds.

54. At t = 472 seconds, CPF2 assigns the jammer against threat 8. Kill assessment begins at t = 481 seconds. The result of kill assessment is that the jammer did not deceive threat 8.

55. At t = 472 seconds, CPF1 assigns the jammer against threat 8. Kill assessment begins at t = 481 seconds. The result of kill assessment is that the jammer did not deceive threat 8.

56. At t = 473 seconds, TRUMP1 rotates 6° to port. The turn should end with the ship heading at 94°. It actually ends at 96°. Chaff cloud 4 is launched from the 110° launcher against threat 1. Kill assessment takes place at t = 498 seconds. The result of kill assessment is that the chaff did not deceive threat 1. The reaction is halted at t = 498 seconds.

57. At t = 473 seconds, TRUMP2 assigns STIR B and the surface-to-air missile system to threat 1. The reaction is confirmed at t = 481 seconds. Missiles 11 and 12 are launched at threat 1. STIR B loses track because threat 1 is destroyed by missile 11 of CPF1. The reaction is halted at t = 496 seconds.

58. At t = 475 seconds, CPF1 rotates 62° to starboard. The turn should end with the ship heading at 35°. It actually ends with the heading at 36°. Chaff cloud 3 is launched from the 45° launcher at threat 5. Kill assessment begins at t = 500 seconds. The result of kill assessment is that threat 5 was not deceived by the chaff. The reaction is halted at t = 500 seconds.

59. At t = 479 seconds, TRUMP1 assigns STIR A and the surface-to-air missile system to threat 5. The reaction is confirmed at t = 481 seconds. Missiles 13 and 14 are launched at threat 5. STIR A loses track because threat 5 is destroyed by missile 5 of CPF2. The reaction is halted at t = 498 seconds.

60. At t = 480 seconds, TRUMP2 assigns STIR A and the gun system to threat 5. The reaction is confirmed at t = 482 seconds. Gun burst 2 is fired at threat 5. STIR A loses track because threat 5 is destroyed by missile 5 of CPF2. The reaction is halted at t = 498 seconds.

61. At t = 482 seconds, CPF2 assigns STIR A and the surface-to-air missile system to threat 5. The reaction is confirmed at t = 484 seconds. Missiles 5 and 6 are launched at threat 5. Kill assessment takes place at t = 500 seconds and the result of kill assessment is that threat 5 is destroyed by missile 5 of CPF2. The reaction is halted at t = 500 seconds.

62. At t = 482 seconds, CPF1 assigns STIR A and the surface-to-air missile system to threat 1. The reaction is confirmed at t = 484 seconds. Missiles 11 and 12 are launched at threat 1. Kill assessment takes place at t = 498 seconds and the result of kill assessment is that threat 1 is destroyed by missile 11 of CPF1. The reaction is halted at t = 498 seconds.

63. At t = 483 seconds, CPF2 rotates 8° to port. The turn should end with the ship heading at 117°. It actually ends at 145° because reactions 65 and 70 begin before reaction 63 ends. Chaff cloud 3 is launched from the 45° launcher against threat 8. The fused track is dropped because threat 8 is destroyed by missile 5 of TRUMP1. The reaction is halted at t = 487 seconds.

64. At t = 483 seconds, TRUMP2 rotates 17° to port. The turn should end with the ship heading at 119°. It actually ends at 118°. Chaff cloud 4 is launched from the 110° launcher against threat 4. The reaction is halted at t = 506 seconds.

65. At t = 484 seconds, CPF2 rotates 20° to port so that STIR B can engage threat 5. The initial heading of CPF2 is 109°. The threat bearing is 89°.

66. At t = 485 seconds, CPF2 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is halted at t = 487 seconds because threat 8 is destroyed by missile 5 of TRUMP1.

67. At t = 485 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 8. The reaction is halted at t = 487 seconds because threat 8 is destroyed by missile 5 of TRUMP1.

68. At t = 486 seconds, TRUMP1 rotates 26° to starboard so that STIR B can engage threat 4. The initial heading of TRUMP1 is 93° and the threat bearing is 107°.

69. At t = 488 seconds, CPF2 assigns STIR B and the gun to threat 5. The reaction is confirmed at t = 490 seconds. The gun fires burst 1 at threat 5 and then STIR B loses track because threat 5 is destroyed by missile 5 of CPF2. The reaction is halted at t = 498 seconds.

70. At t = 488 seconds, CPF2 rotates 21° to port. The turn should end with the ship heading at 141°. It actually ends at 145°. Chaff cloud 4 is deployed from the 110° launcher at threat 4. The fused track is dropped because threat 4 is destroyed by missile 13 of CPF1. The reaction is halted at t = 506 seconds.

71. At t = 489 seconds, TRUMP1 assigns STIR B and the surface-to-air missile system to threat 1. The reaction is confirmed at t = 493 seconds. Missiles 15 and 16 are launched at threat 1. STIR B loses track because threat 1 is destroyed by missile 11 of CPF1. The reaction is halted at t = 496 seconds.

72. At t = 490 seconds, CPF1 assigns STIR B and the surface-to-air missile system to threat 4. The reaction is confirmed at t = 494 seconds. Missiles 13 and 14 are launched at threat 4. Kill assessment takes place at t = 505 seconds and the result of kill assessment is that threat 4 is destroyed by missile 13 of CPF1. The reaction is halted at t = 505 seconds.

73. At t = 495 seconds, CPF1 assigns the CIWS and the CIWS fire-control radar to threat 1. The reaction is halted at t = 498 seconds because threat 1 is destroyed by missile 11 of CPF1.

74. At t = 496 seconds, CPF2 assigns the CIWS and the CIWS fire-control radar to threat 5. The reaction is halted at t = 499 seconds because threat 5 is destroyed by missile 5 of CPF2.

75. At t = 496 seconds, TRUMP1 assigns STIR B and the surface-to-air missile system to threat 4. The reaction is confirmed at t = 500 seconds. Missiles 17 and 18 are

launched at threat 4. STIR B loses track because threat 4 is destroyed by missile 13 of CPF1. The reaction is halted at t = 503 seconds.

76. At t = 498 seconds, TRUMP1 assigns STIR A and the gun to threat 4. The reaction is halted at t = 501 seconds because the gun cannot engage the predicted interception point.

77. At t = 499 seconds, CPF2 assigns STIR B and the gun to threat 5. The reaction is halted at t = 500 seconds because threat 5 is destroyed by missile 5 of CPF2.

78. At t = 499 seconds, CPF2 assigns the CIWS and the CIWS fire-control radar to threat 5. The reaction is halted at t = 499 seconds because threat 5 is destroyed by missile 5 of CPF2.

79. At t = 499 seconds, CPF1 assigns STIR A and the gun to threat 4. The reaction is halted at t = 503 seconds because STIR A lost track of threat 4. It was destroyed by missile 13 of CPF1.

80. At t = 499 seconds, TRUMP1 rotates 53° to port. The turn should end with the ship heading at 120°. Chaff cloud 5 is launched from the 45° launcher at threat 1. The fused track is dropped and the reaction is halted at t = 500 seconds because threat 1 is destroyed by missile 11 of CPF1.

81. At t = 501 seconds, CPF1 rotates 44° to port. The turn should end with a ship heading at 80°. Chaff cloud 4 is launched from the 110° launcher at threat 4. The fused track is dropped and the reaction is halted at t = 505 seconds because threat 4 is destroyed by missile 13 of CPF1.

82. At t = 501 seconds, TRUMP1 rotates 49° to starboard. The turn should end with the ship heading at 21°. Chaff cloud 6 is launched from the 45° launcher at threat 5. The fused track is dropped and the reaction is halted at t = 502 seconds because threat 5 is destroyed by missile 5 of CPF2.

83. At t = 503 seconds, TRUMP1 rotates 50° to port. The turn should end with the ship heading at 120°. Chaff cloud 7 is launched from the 45° launcher at threat 4. The fused track is dropped and the reaction is halted at t = 507 seconds because threat 4 is destroyed by missile 13 of CPF1.

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This document presents an overview of a knowledge-based threat evaluation and weapon assignment (TEWA) testbed referred to as the AAW simulator. This testbed is used to generate weapon assignment reactions where the deployment of hardkill and softkill weapons is integrated with ship movements such as rotation. It incorporates efficient weapon assignment algorithms for single and multiple ship cases. Resource allocation results are presented for the knowledge-based TEWA of a single, manoeuverable ship attacked by twelve anti-ship missiles and those of four ships attacked each by a pair of anti-ship missiles.

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